S-3B Flight Data Computer Replacement: A Legacy Systems Challenge

Abstract

The S-3B anti-submarine/surface-warfare airplane has been in service since the early 1970s. Over time, the materiel condition of the integrated autopilot system consistently degraded. By the late 1990s the autopilot mean-time-between-failure was dropping toward 30 hours, with significant impact on mission readiness. A new digital autopilot computer was planned to replace the central component, yet without replacing any of the controls, sensors, actuators, or wiring. During the upgrade design and integration, numerous challenges were met successfully, ranging from lack of original documentation to high-failure-rate external components. The upgraded autopilot is currently being fielded in the S-3B fleet, resulting in improved readiness, better airplane troubleshooting and maintenance, and restoration of lost autopilot functionality. The S-3B autopilot upgrade strategy, process and methods may apply to future upgrades for other legacy systems.

Introduction

The S-3B anti-submarine/surface-warfare airplane has been in service with the United States Navy since the early 1970s. The reliability of the integrated autopilot system was initially low, and over time it further degraded. By the late 1990s the autopilot mean-time-between-failure was around 30 hours, with significant impact on mission readiness. Several initiatives were undertaken to correct the problems but funding was not made available until after the autopilot computer was implicated in a mishap in 1991.

Background

The S-3B Airplane

Figure 1
S-3B Test Airplane

The S-3B, shown in Figure 1, is a carrier based, subsonic, high wing aircraft, operated in the 35,000 to 50,000 lb gross weight class, and powered by two high-bypass turbofan engines. The aircraft mission system equipment is designed to detect, analyze, and attack surface and subsurface targets. The crew compartment is comprised of side-by-side pilot and copilot stations, behind which are located the side-by-side Sensor Operator and Tactical Coordinator stations. The aircraft is designed to be operated by a single pilot through the use of conventional flight controls (including a center control stick, throttles and rudder pedals). A complete set of flight controls are also provided for the copilot. The primary flight control system consists of elevators, a trimmable horizontal stabilizer, ailerons and spoilers, and a rudder. In normal operation, the flight control system is irreversible and powered by two independent hydraulic systems. An artificial feel system is incorporated to provide the pilot with simulated control forces. The secondary flight control system consists of wing flaps, speedbrakes and the pitch, roll and yaw trim systems. Leading and trailing edge flaps are used for takeoff, slow speed maneuvering and normal landing. The two upper and single lower surface spoiler panels on each wing are extended differentially for added roll control or can be extended simultaneously for use as speedbrakes. A Direct Lift Control system, which uses the upper inboard spoilers, provides rapid downward corrections to flight path during landing approaches. Automatic and manual pitch trim are provided by an electrical actuator deflecting the horizontal stabilizer; manual roll trim is accomplished by an electrically-commanded hydraulic actuator repositioning the ailerons and spoilers; and yaw trim is adjusted by a manually operated mechanical trim tab on the rudder. Of these systems, the primary control surfaces and pitch trim are controlled by the autopilot to provide pilot relief, automatic steering, speed control, stability augmentation, and automatic carrier landing functions.

Flight Data Computer

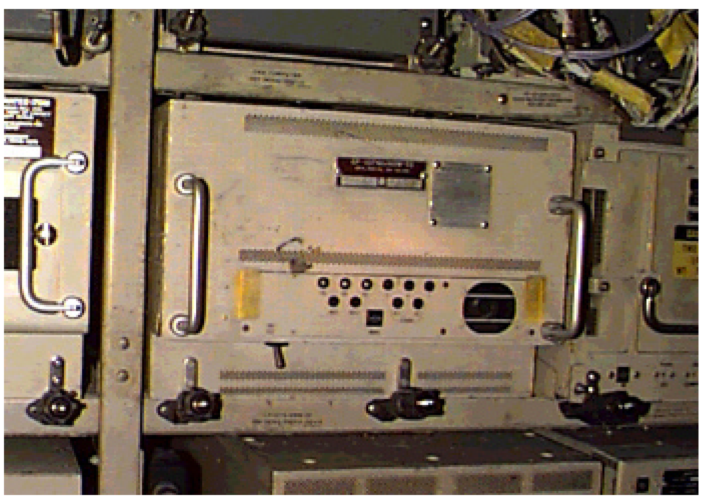


Figure 2
S-3B Flight Data Computer

The Flight Data Computer (FDC), shown in Figure 2, was the primary component of the S-3B Automatic Flight Control System (AFCS), which interfaces directly with over thirty sensors, actuators, control panels, displays, and other airplane systems, using approximately six hundred individual wires.

Figure 3
Autopilot Flight Mode Selector Panel

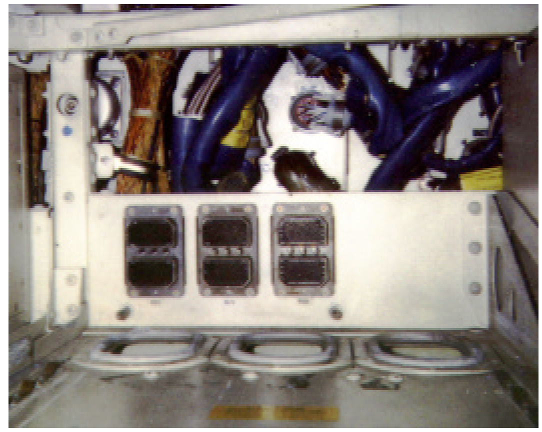


Figure 4
Autopilot Rack Mount
with Six 106-pin Connectors

One of several pilot interface panels is illustrated in Figure 3. The rack space with a complex of six 106-pin connectors is shown in Figure 4. Built in the early 1970s, the analog autopilot computer used primarily analog processing, mixing wire wrap analog circuits for power and control laws and printed circuit technology for built-in test functions. Dual-channel processing and dual-redundant interfaces for most systems provided basic error-checking functionality.

Digital Flight Data Computer

Figure 5
Digital Flight Data Computer

The S-3 Digital Flight Data Computer (DFDC) program was designed to replace the legacy FDC portion of the Automatic Flight Control System (AFCS) with new digital computer hardware and software. The DFDC, shown in Figure 5, was designed as a form, fit, and function replacement for the legacy autopilot. The software-based control laws and logic implemented in the DFDC were designed to provide all of the functions provided by the analog FDC. Deficiencies cited during previous Navy evaluations were considered in designing the replacement computer, with its control laws and logic, redundancy management (RM) and Built-in-Test (BIT) functions. Numerous changes to the flight control laws were made and the replacement autopilot computer has a much more comprehensive RM and BIT design. The Motorola 68020-based DFDC uses surface-mount and printed circuit technology, and all control law, RM and BIT processing is performed via ADA software. All electrical input and output connections are handled with analog-to-digital and digital-to-analog conversion circuitry.

DFDC Integration

Integration Challenges

The replacement autopilot computer was designed by a joint US Navy/Lockheed Martin Aeronautical Systems/Lockheed Martin Control Systems team. The US Navy began specification development in 1993. Initial design of the control laws and software proceeded in parallel with the hardware design. Simulation and hardware interfaces were also designed and built to test the design at various stages of construction. The program included several simulation-only and ground-test-only versions of the software, prior to the planned first flight version. Between 1997 and 2000, seven major software versions (approximately 80,000 lines of ADA code each) and three prototype hardware units were delivered and evaluated, until the production release to the fleet in late 2000. During this time period, the following challenges were addressed.

Lack Of Background Knowledge

The airframe contractor and the government did not have current autopilot documentation for control laws, redundancy management, built-in-test, and interfaces; this information was critical for preparation of replacement autopilot computer specifications (which defined the required functionality) and the interface control document (which completely defined the required electrical interface).

Poor Legacy System Documentation

Years before the start of the replacement autopilot computer program, the airframe contractor closed the plant where the design and development work on the S-3 was originally performed, and moved all related documentation. Some information was lost during the move, and the knowledge required to access the remaining information was also lost. Due to the age of the platform, most design and test engineers had already retired.

Nonexistent Maintenance Of Disconnected Systems

In 1991, the roll axis of the autopilot was implicated as a causal factor in an airplane mishap. As a result, all roll functions of the autopilot were physically disabled in an attempt to prevent further mishaps. A corresponding portion of the overall system functionality was lost, and with it the requirement for maintaining roll-axis-related subsystems was removed. As the airplane continued to age, this disconnected or unused equipment fell into further disrepair. For both the development and test program and for the fleet-wide introduction of the replacement autopilot, these un-maintained systems required extensive troubleshooting and repair.

Poor Maintenance Of Failure-Prone Systems

Numerous legacy autopilot system components typically experienced high failure rates. Faced with limited supply and repair funding, the fleet designated only a few system functions as essential for flight operations. Other functions were designated non-essential, and repair of the system was often limited to essential functions only. This led to a general decline in the state of repair of the overall system. The first task during development testing was returning the test platform to an original design condition with fully functional subsystems. Naturally this same problem affects introduction of the replacement system into the fleet, as each airplane must be fully repaired before being upgraded.

Inadequate Fault Isolation

The legacy autopilot computer fault isolation was limited to ten "bit balls", one self-check, one for each flight control and engine control servo, and one each for four external sensors. System maintenance with this severely limited troubleshooting information was extremely difficult, and more art than science. Finding and fixing a problem was often a process of trial and error box swaps, or finding a single broken wire among six hundred others via end-to-end wiring checks. The troubleshooting difficulty not only complicated fleet maintenance procedures but also slowed preparation of the test airplane.

Difficulty Procuring "Golden" Legacy Equipment For Development Testing

Related to the lack of background knowledge, the first challenge in designing a replacement autopilot computer was fully understanding the operation of the legacy system. However, this required a perfectly-functioning legacy system, which presented a significant challenge considering that the reasons for legacy system replacement included poor maintainability and disconnected subsystems.

Old Airplane Systems Interfacing With New Equipment

The replacement autopilot computer had to be designed to gracefully handle very poorly maintained and aging subsystems. For example, the legacy subsystems had large signal level variations between the two redundant channels of the autopilot system. These so-called "miscompares" caused challenges in designing self-test comparisons and preventing operational transients. The high failure rate of legacy subsystems impacted the availability and functionality of the new equipment. Equally challenging was designing a system that would handle the wide variation of electrical and mechanical characteristics across the entire fleet of 30-year-old airplanes.

Redundancy Concerns

Due to the poor maintenance and system age, single-channel (non-redundant) operation was the norm in the fleet, but the replacement system was designed to require dual-channel operations to eliminate safety concerns. Later in the program, it became apparent that requiring dual-channel operations would severely impact fleet readiness, as the fleet did not have the maintenance budget to repair every failed or marginal system on every aircraft. Changes to the software were made, such as using cockpit indications to distinguish between safety-critical and less severe faults, as well as opening up some tolerances where appropriate. These changes were required to permit appropriate non-redundant operation, while helping identify critical faults where redundancy was mandatory.

Integration Solutions

As the replacement autopilot computer development proceeded, a number of solutions were implemented to overcome the challenges.

Research on Legacy System

The first task in designing the new autopilot was comprehensive research into the legacy system. Missing documents had to be reconstructed or replaced through research and testing of the legacy system. Some interviews were conducted with engineers who had worked on the legacy system introduction. Documents were compiled which detailed the system philosophy of operation, the design, and construction details.

Evaluation of Legacy Sensors and Actuators

Critical flight control and autopilot components were provided to the contractor by the government. Detailed measurements were taken to quantify the input and output characteristics of these subsystems. Many changes to the built-in-test and redundancy tolerances were made early in the design as a result of these measurements.

Maintenance Trainer Testing

The Navy maintains an "iron bird" maintenance trainer, consisting of all key subsystems of the airplane. This maintenance trainer was used heavily, initially to research the legacy system operation and characteristics, and later to validate the electrical and physical interface of the replacement computer. Having a comprehensive hydro-mechanical and electrical test bed without risking a flight-worthy aircraft was invaluable during the early design cycle.

Software Simulation

During the contractor's design and construction of the replacement autopilot, a parallel Navy effort was conducted to build a high-fidelity pilot-in-the-loop and offline FORTRAN simulation of the autopilot system. The simulation setup is schematically illustrated in Figure 6, and the cockpit and engineering stations are shown in Figure 7.

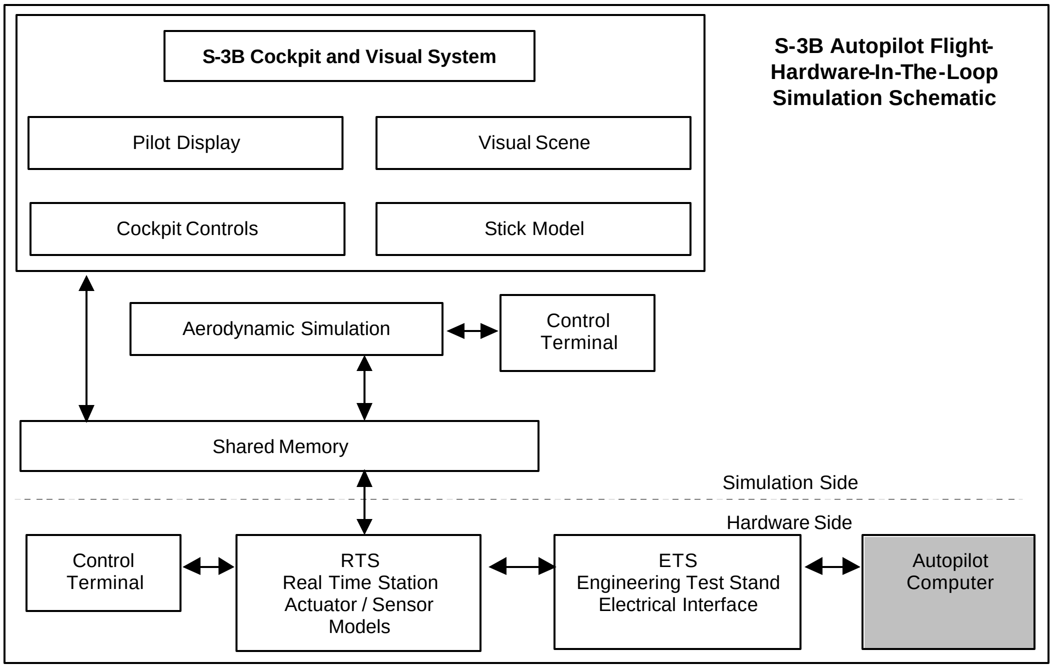


Figure 6
S-3 Hardware-In-The-Loop Simulation Schematic

Figure 7
S-3B Flight Simulation Station

The contractor used a software tool called BEACON to automatically generate flight software based on design software flow diagrams. During development, BEACON generated ADA code for the autopilot computer, and also separately generated FORTRAN code for the simulator. The FORTRAN code was integrated directly into the simulation, allowing piloted and automated evaluation of the proposed design. Although the focus of this effort was to validate and tune the replacement autopilot design, several issues with the legacy autopilot were discovered and corrections were made in the replacement autopilot prior to delivery of the final software.

Hardware Test Stand

The contractor/Navy team constructed a hardware test stand, shown schematically in Figure 6, to evaluate the autopilot computer directly and in conjunction with a flight simulation. An Engineering Test Stand (ETS) was constructed by the contractor to permit detailed electrical interface testing of the autopilot computer. The Navy constructed a test facility based on an Applied Dynamics International Real-Time Station (RTS). This test facility simulated all sensors, actuators and interface panels, including dynamic models of actuator response. As a combination, the ETS/RTS system allowed both the legacy and replacement autopilot computers to be stimulated in a flexible yet realistic simulation of the airplane. The RTS host computer was programmed to allow manual and automated tests to be executed. Static and dynamic testing allowed comprehensive mapping of the input and output characteristics. Results of typical variations on the inputs could be explored. Possible failure modes could be exhaustively tested in the lab without endangering aircrew or airplanes.

Hardware-in-the-Loop Simulation

In addition to the FORTRAN simulation, provisions were made to connect the ETS/RTS to the simulation host computer, to allow the autopilot computer to be tested hardware-in-the-loop. The interconnections are illustrated in Figure 6. This permitted both automated and piloted evaluation of the actual autopilot hardware and software in a lab environment. Since both the legacy and replacement units could be evaluated, several corrections to previously unknown deficiencies in the legacy autopilot were identified and fixes were evaluated and incorporated into the replacement autopilot.

Legacy and Replacement Side-by-Side Evaluation

The ability to evaluate both legacy and replacement autopilots in the simulator not only helped uncover deficiencies in the replacement autopilot but also improved understanding of the baseline system. Several "gray" areas in the baseline documentation were clarified through careful simulator testing. Furthermore, all planned automated simulation tests could be run against the baseline unit to verify and validate the test procedures and expected results.

Detailed system block diagrams

As research and testing revealed the total operation of the legacy autopilot system, detailed block diagrams were constructed showing all system modes and control laws. Block diagrams of the proposed replacement autopilot were also drawn based upon the legacy autopilot. These diagrams were included in the design specifications for the replacement autopilot, and became part of the deliverable documentation. These diagrams proved indispensable in later troubleshooting and deficiency resolution.

Integration Lessons Learned

The following lessons regarding upgrading legacy systems were learned during the replacement autopilot computer integration.

Background Research and Documentation

Do not rely on the contractor to retain information that is essential for development of replacement components for critical systems. The customer should contractually require delivery of all critical data and archive this data.

Research the interface and design philosophy of the legacy system before starting the design process. Incorrect, outdated, or unavailable documentation can lead to incorrect design that may be costly to reengineer late in the evaluation cycle.

Simulation

Build simulations early in the development process. If possible, build a hardware-in-the-loop simulation for back-to-back evaluation of legacy and replacement systems.

When programmed computers are used in the design, obtain the internal software (or some true representation compatible with simulation tools) for constructing the simulation; this permits deeper investigation into software characteristics than is possible with purely in-place (such as aircraft-based) testing.

Installation and Integration

Anticipate and plan for difficulty installing the system on legacy platforms. Returning a legacy platform to design specifications for test purposes ("grooming" the system) will be challenging, especially if obsolete or disconnected functionality is re-enabled by the new system.

Fielding a replacement system will require restoring each platform to like-new status. Anticipate maintenance personnel resistance to required maintenance efforts, especially if long-abandoned maintenance is required. Maintenance practices have very high inertia that must be overcome to successfully field a new system.

Upgrades often involve new or upgraded functions, or re-enabling long-lost functions. Anticipate user resistance to new or restored functionality, and more importantly, anticipate having to overcome "the old way" of using the system. Users, and pilots in particular, learn to compensate for undesirable behavior in unexpected ways, and this "misuse" of the new system may have unintended consequences on system operation.

Coordinating Multiple Upgrades

Wherever possible, coordinate the requirements and designs when upgrading multiple systems. Legacy platforms often upgrade systems in blocks. Many times, system integration can improve the overall user interface and system flexibility, but only if the upgrades are made compatible and can be interconnected. The sooner this coordination occurs in the design cycle, the more cost-effective the integration.

Make provisions in the design for a standardized digital interface, such as the MIL-STD-1553B bus; select the interface based on whatever is currently in use elsewhere on the system.

Final Program Documentation

Document the operation of the system, and particularly the deficiencies, with the viewpoint that such documentation may be the only available resources for a future upgrade. Corporate knowledge is priceless, and must be preserved before a team disbands.

Insist on thorough contractor-deliverable documentation. Do not allow this seemingly secondary product to be trimmed for short-term cash savings; instead, anticipate that the current documentation costs will be much lower than future costs required to reconstruct missing documentation. Assume that this documentation will be critical to future upgrades.

Planning for the Future

Anticipate future upgrades. Even a replacement unit in a legacy platform stands a good chance of being replaced in the future. As budgets for new systems dwindle, older systems are being pressed into extended service, and some components will see several upgrades over the life of the platform.

Don't treat new systems as discrete components. Provide for expandability and integration even if the system is a standalone part of a larger system. This provides maximum flexibility for the future.

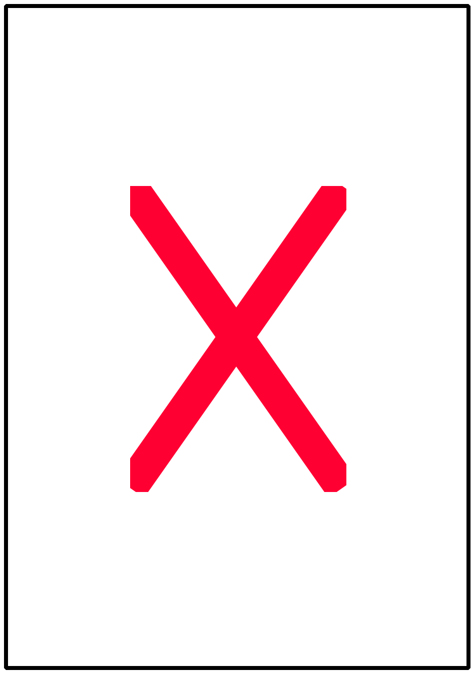
Treat each design as if it will one day be a legacy system itself. Thorough documentation and expandability will limit future costs.

Each new system will probably require minor upgrades shortly after fielding. From the beginning of the process, plan and budget for near-term "follow-on" upgrades, and staunchly defend this funding.

Summary

The S-3B Digital Flight Data Computer (DFDC) Team successfully fielded a replacement autopilot computer for the S-3B airplane, despite numerous and complex challenges ranging from limited documentation to poorly maintained legacy systems. The S-3B has 1960's flight control technology, high maintenance costs, and outdated equipment, which the US Navy is constantly and successfully upgrading. Thus, the S-3B airplane is a prototypical legacy systems challenge. In turn, the DFDC program typified the problems to be expected during a legacy system replacement. The lessons learned during the DFDC program can be applied to upgrading any legacy system, and the sooner they are applied the easier the upgrade process will be. Similarly, if these lessons are applied to the procurement of new platforms, the inevitable future upgrades will be easier, faster and less costly.

Personal Information



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Mr. Munday has been employed by the US Navy at NAWCAD Patuxent River since his graduation from Virginia Tech in 1990, and has been involved in simulation and flight testing on the T-45A, AV-8B, A–4J, and most recently the S-3B. He has authored and participated in publication of numerous technical reports on tests of those model simulators and aircraft.

Mr. Munday was the Test and Evaluation (T&E) Team Leader for the Digital Flight Data Computer (DFDC) replacement autopilot computer during initial development, and again during final integration flight testing. He more recently assumed the DFDC Team Leader position, responsible for final reporting and T&E oversight of ongoing fleet incorporation of the DFDC into the S-3B. He is also currently involved in upgrade efforts on the S-3B Operational Flight Trainer and the S-3B Pitch Rate Sensor.

Mr. Munday also maintains a home business based on programming and marketing music-related software. His Windows-based products include a music transposition utility and a song database application.